**Measuring the Sensitivity of the GOES-8/9 Sounder**

**To Atmospheric Boundary Layer Conditions**

An unsolicited proposal submitted to
DOC/NOAA/NWS W/OM
Office of Meteorology
attn: Ron Gird
1325 East-West Highway
Silver Spring, MD 20910

by
*Goddard Space Flight Center*


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| FY98 Funding Request: | $122k |
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# Measuring the Sensitivity of the GOES-8/9 Sounder To Atmospheric Boundary Layer Conditions


## ABSTRACT

The infrared Sounder on the current generation of NOAA's Geosynchronous Operational Environmental Satellites (GOES-8/9) is designed to be sensitive to mesocale gradients in temperature and moisture. Seven new channels were added to the previous VAS 12-channel design, providing radiometric sensitivity to atmospheric boundary layer conditions — similar channels appear darker where there is more moisture to absorb upwelling radiation and appear brighter where the air is warmer. However, there are factors that limit the information from small differences among similar channels: radiometric noise, calibration errors, channel misregstration, surface emissivity, clouds, reflected sunlight, look-angle, biased absorption coefficients, differences between satellites, land-ocean biases, etc..

We propose to measure the effective sensitivity of the Sounder channels to boundary conditions by using case studies (field experiments) where accurate in-situ measurements of mesoscale boundary layer conditions are available during the GOES Sounder operations in the late 1990's. In addition to field experiments, point-sites (radiosondes) will be used where a long time-series provide a statistically significant sample. The methodolgy will be mainly statistical, with physically motivated models for the expected sensitivity and biases of the satellite and in-situ conditions. Once the correction algorithms and correlation coefficients are reliably established from operational GOES data, we will make Sounder-based derived image products for estimating boundary layer temperature and moisture values for a realtime "nowcasting" mode which could be made operational in a typical unix workstation. We will also investigate the use of coincident Imager data for optimizing the GOES retrievals. NOAA willing, the algorithm for calculating boundary layer products will be ported to a NWS/OM unix workstation that can access the realtime Sounder data at NASA-GSFC over the internet.

As a side-study, we will use the same methodology to investigate the possbility of detecting mesocale concentrations of ozone within the troposphere using the 9.7 micron infrared ozone-sensitive channel on the GOES-8/9 Sounders. A GOES ozone algorithm will need supplemental measurement of total ozone from a polar-orbiting instrument (TOMS, SSBUV or TOVS) to provide a correction for the bulk of the ozone which is in the stratosphere.

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# Measuring the Sensitivity of the GOES-8/9 Sounder To Atmospheric Boundary Layer Conditions

## INTRODUCTION

The infrared Sounder on the current generation of NOAA's Geosynchronous Operational Environmental Satellites (GOES-8/9) is designed to be sensitive to mesoscale gradients in temperature and moisture. Seven new channels were added to the previous VAS 12-channel design, providing radiometric sensitivity to atmospheric boundary layer conditions — similar channels appear darker where there is more moisture to absorb upwelling radiation and appear brighter where the air is warmer. However, there are factors that limit the information from small differences among similar channels: radiometric noise, calibration errors, channel misregstration, surface emissivity, clouds, reflected sunlight, look-angle, biased absorption coefficients, differences between satellites, land-ocean biases, etc..

## The GOES Sounder

The GOES-8/9 Sounders carry 18 infrared channels and 1 visible channel designed for observing at mesoscale resolution (see Table 1).

Many of the GOES Sounder channels are similar to corresponding HIRS tropospheric channels used on the NOAA polar orbiter, but some channels were explicitly designed for mesoscale soundings and for improvements to the previous VAS instrument. For instance, during daylight hours, the low-resolution visible channel will be used to help retrievals in partly cloudy fields.

| DETECTOR | CHANNEL | WAVELENGTH micron ($cm^{-1}$) | PURPOSE |
|---|---|---|---|
| longwave | 1* | 14.71 (680) | stratosphere temp. |
| " | 2* | 14.37 (696) | tropopause temp. |
| " | 3* | 14.06 (711) | upper-level temp. |
| " | 4* | 13.64 (733) | mid-level temp. |
| " | 5* | 13.37 (748) | low-level temp. |
| " | 6* | 12.66 (790) | total precipitable water |
| " | 7 | 12.02 (832) | sfc temp. & moisture |
| correction. | | | |
| midwave | 8* | 11.03 (907) | sfc temp. |
| " | 9 | 9.71 (1030) | total ozone |
| " | 10† | 7.43 (1345) | low-level moisture |
| " | 11* | 7.02 (1425) | mid-level moisture |
| " | 12* | 6.51 (1535) | upper-level moisture |
| shortwave | 13 | 4.57 (2188) | low-level temp. |
| " | 14* | 4.52 (2210) | mid-level temp. |
| " | 15* | 4.45 (2245) | upper-level temp. |
| " | 16† | 4.13 (2420) | "boundary layer" temp. |
| " | 17* | 3.98 (2513) | sfc temp. |
| " | 18 | 3.74 (2671) | sfc temp. & moisture |
| correction. | | | |
| visible | 19 | 0.967 (14367) | cloud |

* These channels approximately correspond to current VAS channels.
† These channels are new and are not on HIRS.

LIMITS:
- Channels 16, 17 and 18 are affected by reflected sunlight.
- Channel 10 is affected by methane absorption.
- Channel 5 is affected by water vapor absorption.
- Channel 9 is affected by water vapor and surface brightness.
- Channel 19 is dark at night.

TABLE 1: Design of the GOES-8/9 Sounder channels and main spectral limitations.

Figure 1 presents an estimate of the net sensitivity of the observed brightness temperature in each of the Sounder's infrared channels to a small change (1° increase) in the surface temperature, atmospheric temperature, and atmospheric dewpoint, respectively. Dewpoint sensitivity is negative because an increase in water vapor decreases the upwelling radiance. Non-linear effects in the radiation transfer equation result in net sensitivities that can be either greater or less than 1K per 1°C. Figure 1 is based on line-by-line and continuum molecular cross-sections calculated using the U.S. Standard Atmosphere, which is a rather smooth, dry, clear and cold profile compared to typical pre-storm conditions over the United States.

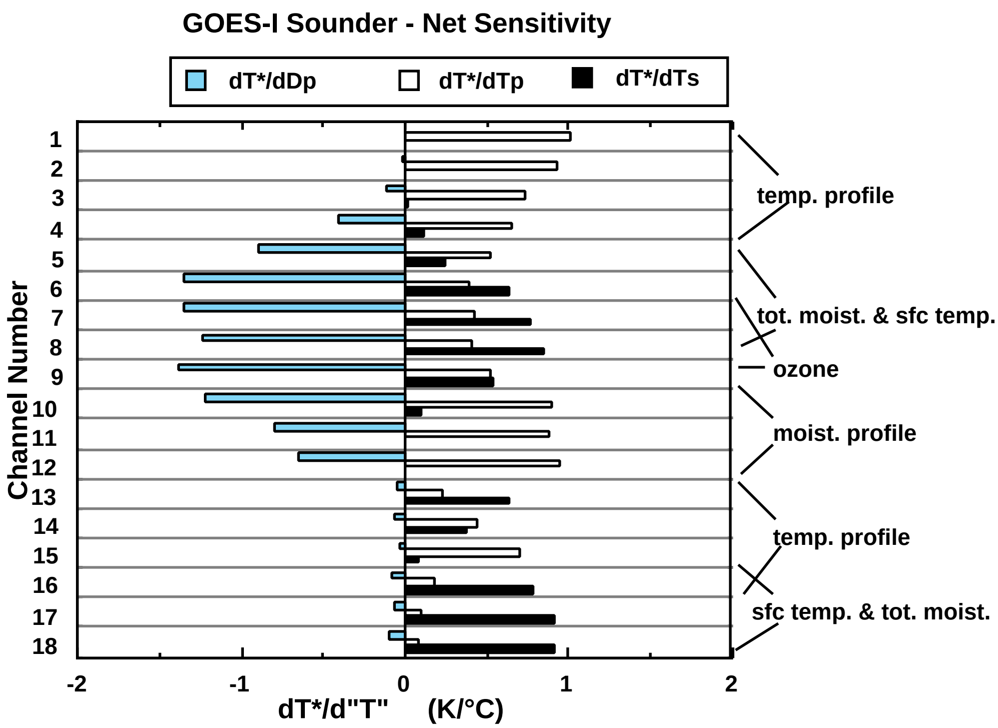


FIG. 1. Net sensitivity of the brightness temperature (T*, Kelvin) in each GOES-I/M Sounder channel to a 1°C increase in atmospheric dewpoint (Dp, grey bars), atmospheric temperature (Tp, white bars) or surface temperature (Ts, black bars).

Fig. 1 lets us see that grouping a few channels together in order to identify them with a simple product is conceptually useful, but accurate retrievals of any single atmospheric parameter will actually require the simultaneous use of most of the Sounder channels.

Fig. 2 presents very early images of eastern CONUS from the GOES-8 Sounder channels, grouped together to indicate how they provide layer-average information about temperature, moisture and ozone. Atmospheric informatio is dominated by cloud top and surface temperatures. With the help of the corresponding Imager channels at higher spatial resolution, cloudy areas should be more reliably identified.

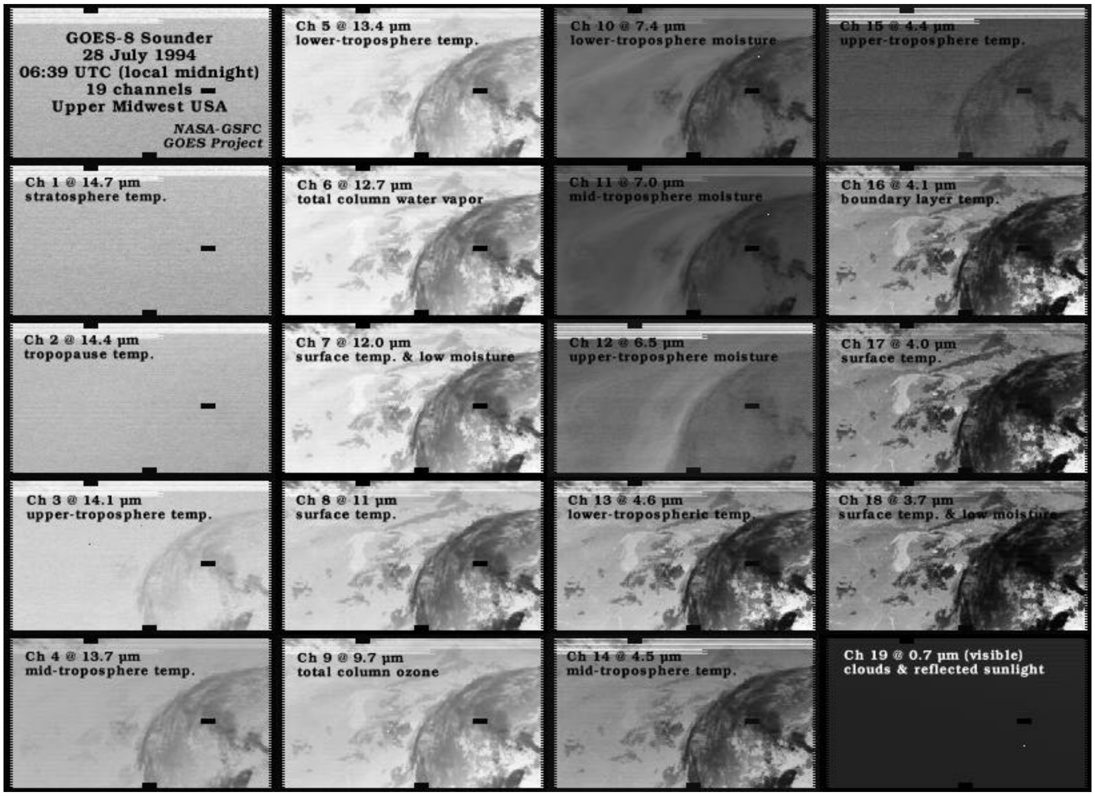


FIG. 2. Images from the GOES-8 Sounder's channels, converted to brightness temperature and presented on the same greyscale.

The following sections present the weighting functions for these sounding channels, and discuss the relationships among them.

## Temperature Profile Soundings

Temperature soundings from the standard 13 to 15 micron channels will be enhanced by the use of three shortwave channels from 4.4 to 4.6 micron and a new nitrogen continuum channel at 4.1 micron to provide more accurate temperature soundings in the lower troposphere and useful sensitivity to the boundary layer. Figure 3 presents the weighting functions for these longwave and shortwave temperature sounding channels.

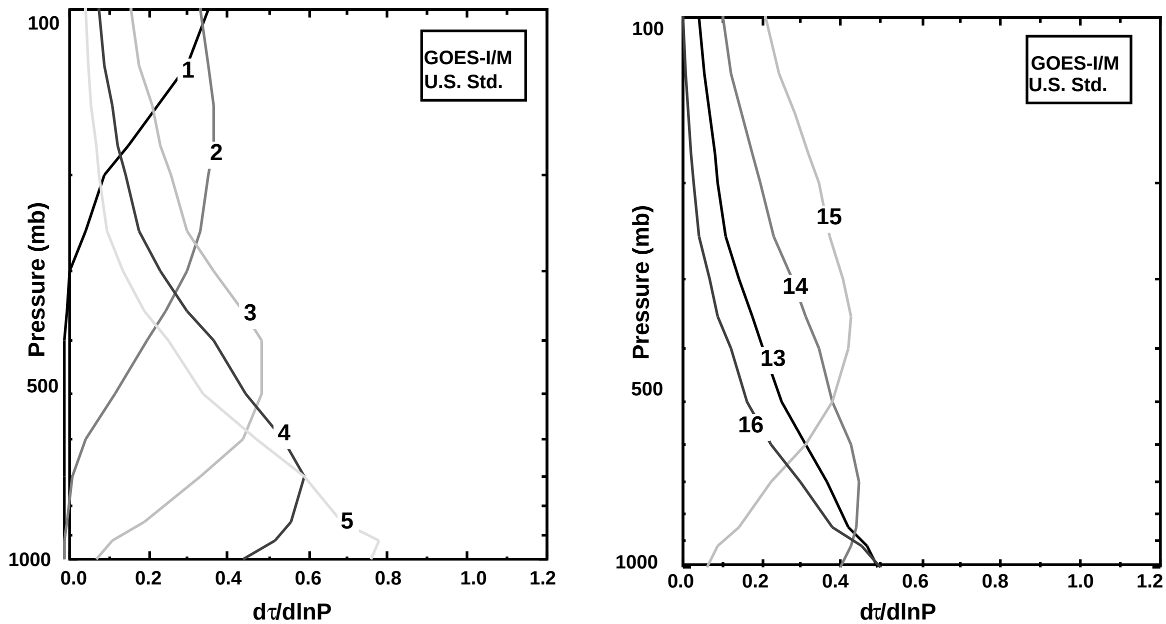


FIG. 3. Transmittance (t) weighting functions for the GOES-I/M Sounder's longwave and shortwave channels intended for temperature profiling.

As an additional data product from these channels, "$CO_2$ sliced" cloud altitudes can be estimated by finding the upper-level temperature-sounding channel in Fig. 3 at which a cloud fades from visibility (Menzel et al., 1983).

### Surface Temperature And "Boundary Layer" Soundings

Figure 4 presents the weighting functions for the longwave "split window" at 11, 12 and 12.7 micron and shortwave "split window" at 3.7, 3.9 and 4.5 micron, which will provide estimates of surface temperature, low-level temperature and low-level water vapor amounts.

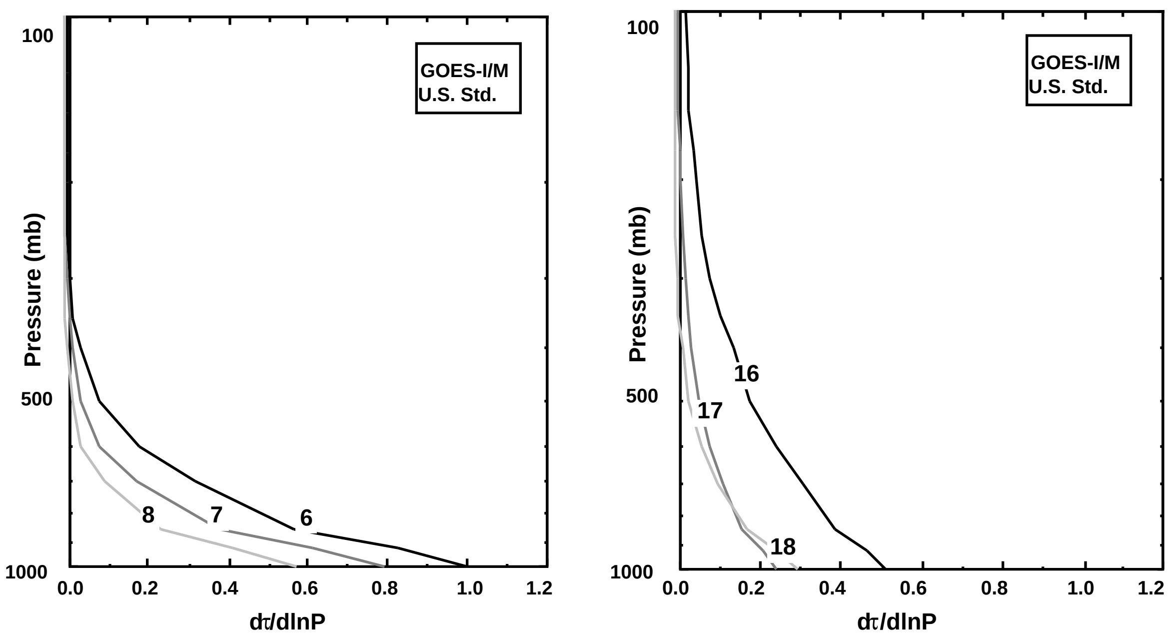


FIG. 4. Transmittance (t) weighting functions for the GOES-I/M Sounder's longwave and shortwave channels intended for determining surface temperature (with moisture corrections), precipitable water, and temperature in the lower atmosphere.

Total precipitable water can be computed easily using "split window" channels alone (Chesters et al., 1983). A few low-level temperature-profiling channels and/or surface observations are also helpful in reducing errors in total precipitable water soundings (Robinson et al., 1986).

## Water Vapor Profile And Total Ozone Soundings

Figure 5 presents the weighting functions for the GOES-I Sounder's "rare gas" channels observing upper air water vapor and ozone. The three water vapor channels in the bandpass from 6.5 to 7.4 micron will parse the vertical structure of the upper-air moisture streaks observed by the GOES-I Imager in its broadband 6.7 micron channel. The 9.7 micron channel will monitor total ozone amounts and provide ozone absorption corrections for the traditional longwave temperature sounding channels. Because the 9.7 micron ozone channel is semi-transparent, it requires corrections for the surface brightness and water vapor continuum from the 11 and 12 micron channels and corrections for the upper air temperature from the 15 micron channels, two of which are included in Figure 4.

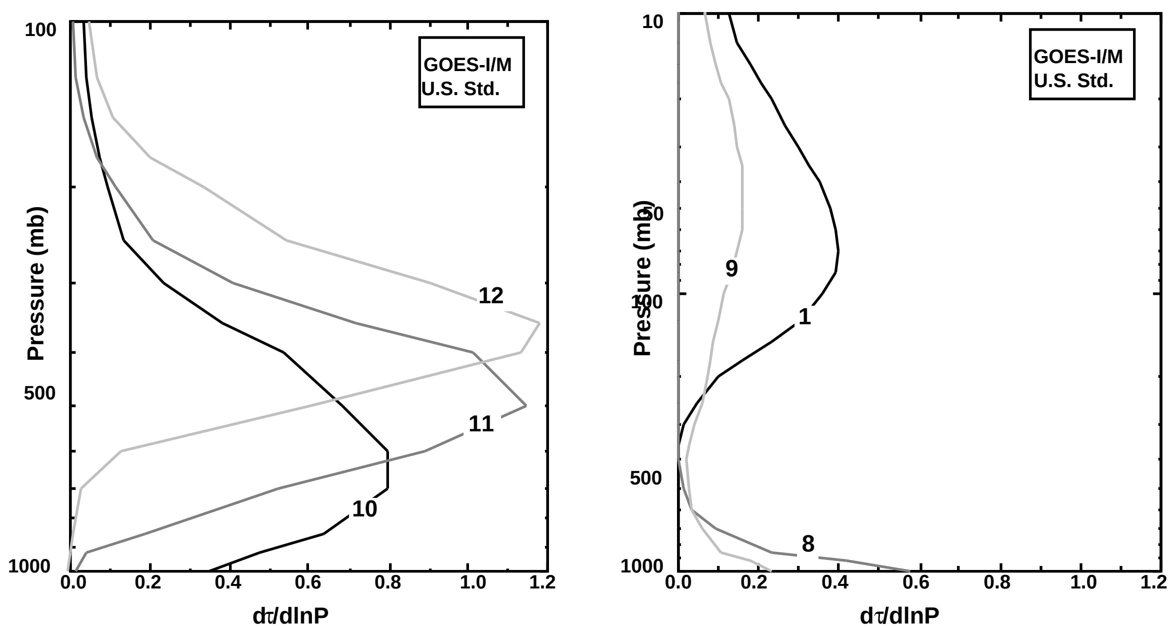


FIG. 5. Transmittance (t) weighting functions for the GOES-I/M Sounder's midwave channels intended for water vapor profiling and total ozone monitoring.

The upper-air water vapor patterns observed in the VAS 6.7 micron imagery have been useful for analyzing pre-convective conditions (Petersen et al., 1984). The 7.4 micron band (channel 10) provides important sensitivity to water vapor near 700 mb, which is lacking in the VAS. The three upper-air water vapor channels should provide enough data to retrieve reliable moisture profiles throughout the troposphere.

Total ozone is often observed to be enhanced during cyclone development (Uccellini et al., 1985). The Sounder can provide continuous ozone observations without the solar illumination and time-of-day restrictions suffered by ultraviolet sensors.

**PRIOR RESEARCH ON RELATED WORK**

The unique aspect of data products from the GOES Sounder stems from the continuous, hourly day/night coverage over the United States at 10 km resolution, a form that lends itself directly to the timely delivery of parameters in an analyzed or image format. Figure 6 shows the conceptual data flow from the atmosphere to the Sounder, through the ground system, retrieval algorithm and data distribution system, resulting in a regular time-series of data products in an easily viewed format. In particular, stable calibration and regular, continuous observations will make it possible for GOES-I data products to provide time-derivatives (trends or "tendancies") in addition to time-lapse snapshots (Chesters et al., 1986) and horizontal gradients in the meteorological parameters that are useful to forecasters (Mostek et al., 1986)

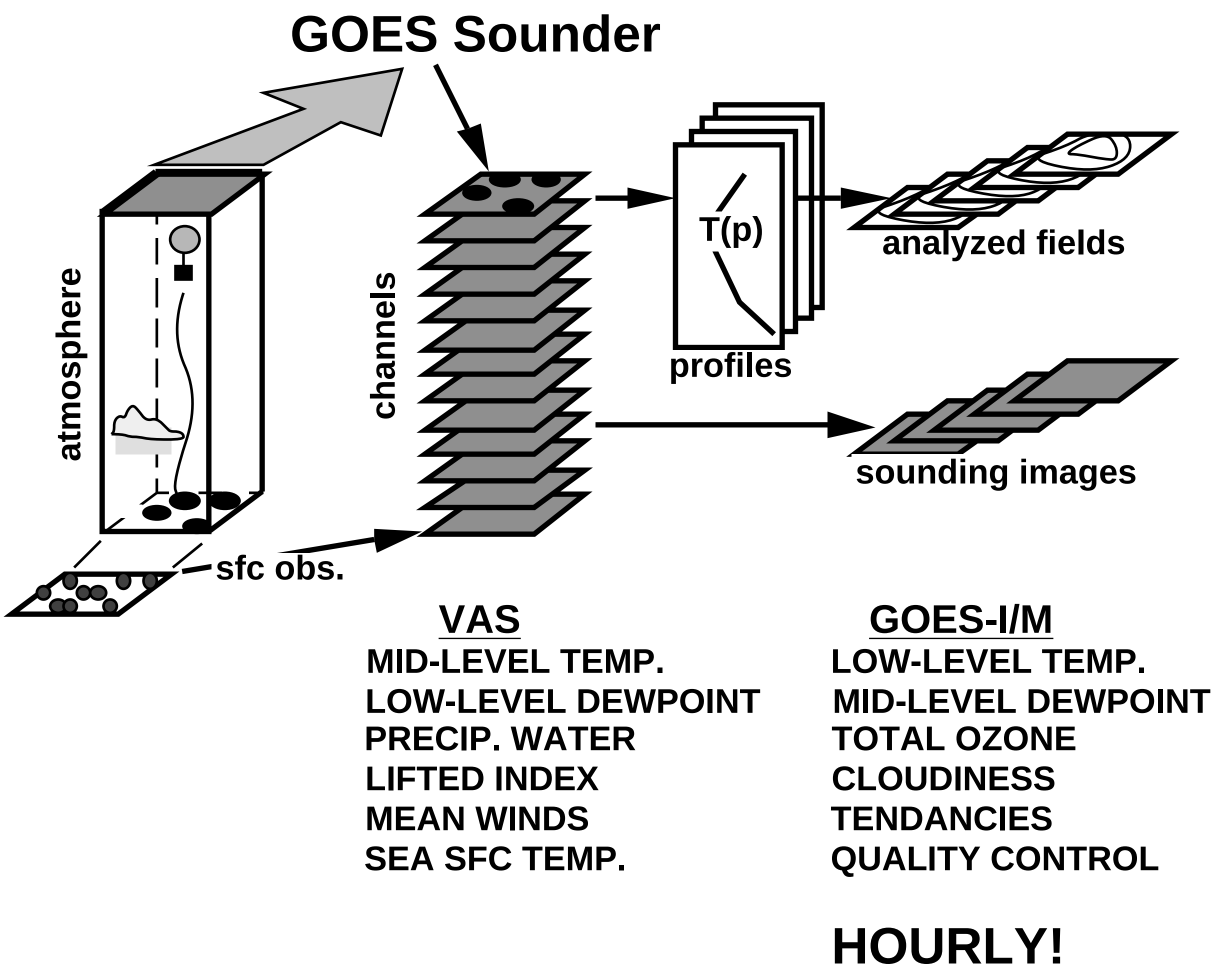


FIG. 6. Conceptual flow of GOES-I data products from the atmosphere and through the Sounder, a ground system, a retrieval algorithm, and a realtime data distribution network providing a ready-to-use format. Sounding images at hourly intervals have been computed from VAS channels at realtime rates using a minicomputer (Chesters et al., 1986).

## PROPOSED RESEARCH

### Temperature and Mositure

We propose to measure the effective sensitivity of the Sounder channels to boundary conditions by using case studies (field experiments) where accurate in-situ measurements of mesoscale boundary layer conditions are available during the GOES Sounder operations in the late 1990's. For example, we are currently collecting GOES data during the ARESE (ARM Enhanced Shortwave Experiment) aircraft flights over the well-instrumented ARM (Atmospheric Radaition Monitors) site operated by the Department of Energy (DOE) at the Kansas/Oklahoma border. In the spring of 1996, there will be a similar set of NASA aircraft experiments studying cirrus cloud physics. In addition to field experiments, point-sites (radiosondes) will be used where a long time-series provide a statistically significant sample.

The methodolgy will be mainly statistical, with physically motivated and/or artificially intelligent models using the expected sensitivity and biases of the satellite and in-situ conditions. Prior work on the production of imagelike realtime data products from the VAS Sounder (Chesters et al., 1986) is the conceptual basis for this proposal. Therefore, a reprint of this reference publication is attached.

Cloud-clearing with the use of higher resolution Imager data will be developed. This experiment will be unique, since NOAA-NESDIS apparently has no plan to merge the inputs from the Imager and Sounder for optimizing atmospheric retrievals.

Once the correction algorithms and correlation coefficients are reliably established from operational GOES data, we will make Sounder-based derived image products for estimating boundary layer temperature and moisture values for a realtime "nowcasting" mode which could be made operational in a typical unix workstation.

### Ozone in the Troposphere

As a side-study, we will use the same methodology to investigate the possbility of detecting mesoscale concentrations of ozone within the troposphere using the 9.7 micron infrared ozone-sensitive channel on the GOES-8/9 Sounders. Total column ozone is reliably measured using the same channel in the TOVS satellite suite (Chesters and Neuendorffer, 1990, -91). The 9.7 micron thermal infrared channel is especially sensitive to the cold ozone at the bottom of the stratosphere, so it is a good indicator of a lowered tropopause.

A GOES ozone algorithm will need supplemental measurement of total ozone from a polar-orbiting instrument (TOMS, SSBUV or TOVS) to provide a correction for the bulk of the warm ozone which is hard to detect thermally at the top of the stratosphere, where the temperature is comparable to the surface.

## ANTICIPATED RESULTS

### Temperature and Mositure

Once the correction algorithms and correlation coefficients are reliably established from operational GOES data, we will make Sounder-based derived image products for estimating boundary layer temperature and moisture values for a realtime "nowcasting" mode which could be made operational in a typical unix workstation.

The validity of the results will be established by dependent statistics (e.g. variance reductions, residual RMS errors, patterns of good- and bad-fits), and by independent statistics (RMS errors with respect to independent in-situ observations).

NOAA willing, the algorithm for calculating boundary layer products will be ported to a NWS/OM unix workstation that can access the realtime Sounder data at NASA-GSFC over the internet.

### Ozone in the Troposphere?

A GOES Sounder-based realtime mesoscale ozone product would be useful to the EPA in monitoring pollution episodes over the United States. The P.I. has been previously approached by the Council of Governments, who are interested in this GOES product, which can be developed as a low-cost spin-off of the boundary layer methodology.

## MANAGEMENT APPROACH

### Schedule

The nominal starting date for theis effort did not account for government shutdowns and delayed funding in FY96. The actual starting date for this effort is continent upon:

funding
manpower

Once funding is assured (mid-CY96?), it could take 3 months to hire a qualified co-investigator under contracting arrangements forced by the new NASA-HQ plan for farming out work to science institutes (see the “Housing” section, below).

The effort is expected to take 3 years, with quarterly progress reports and anual reviews. A course of research is outlined below, becoming less definite in the later years, when the course will be refined as the strengths and weaknesses of the GOES Sounder are discovered, and as the NWS develops specific interests in the Sounder products:

Year 1 -- Setup system, and train Co-Investigator to use GOES data

1.1 Set up computers, data gathering and internet display; create nominal products using simple channel differences
1.2 Set up forward radiation transfer algorithms, test them using conventional radiosonde data
1.3 Establish physically-based but covariance-tuned products, using conventional radiosondes and/or field experiment data
1.4 Set up quasi-operational soundings, and analyse error budget; publish results, and review plan for next year’s work

Year 2 -- Case studies and advanced algorithms

2.1 Investigate use of Imager data for improving Soundings
2.2 Attack the “tall poles” in the error budget and rework algorithms
2.3 Work with a NWS “client” interested in using Sounder products
2.4 Analyse remaining error budget; publish results, and review plan for next year’s work

Year 3 -- quasi-operational production and validation of Soundings

3.1 Demonstrate portability of data processing to a NWS workstation
3.2 Investigate Sounder sensitivity to ozone concentrations
3.3 Independent validation using in-situ observations and case studies
3.4 Review a year of quasi-operational Sounding products publish results

## Deliverables

The research scheduled above results in:
- quarterly reports, of the quality and style of AMS preprints
- annual reports, in the style of peer-reviewed journal papers
- an internet-accessible web site containing Sounding images
- data processing code ported to a NWS unix workstation

The research will result in Sounder products that display atmospheric parameters extracted from common-sense combinations of “split windows”. The products will be formatted for easy access and interactive display using the internet Web technology. Low-level temperature and moisture are the principal data products, with upper level moisture and ozone a good possibility.

## Resources

### Manpower

Dr. Dennis Chesters will be the Principal Investigator, contributing sufficient time and effort to managing the effort, and providing access to the GOES data and to the computer facilities required to do the work.

Dr. Dennis Chesters has been the GOES Project Scientist for the past 4 years. He has 15 years of experience working with the GOES system, originally the multi-channel VISSR Atmospheric Sounder (10 peer-reviewed publications, Chesters, et al., 1982-89). After that, Dr. Chesters investigated global ozone patterns and accuracies using NASA-TOMS and NOAA-TOVS satellite retievals (Chesters and Kreuger, 1989; Chesters and Neuendorffer, 1990). More recently, he has concentrated on the water vapor variations discovered in NOAA's archive of operational polar-orbiting TOVS soundings (Chesters and Neuendorffer, 1992, Chesters and Sharma, 1992, Salathé and Chesters, 1993). For the GOES Project, Dr. Chesters is currently working with NOAA on the post-launch check-out of the new GOES-8/9 satellites (Chesters, 1989), and he is working on a development plan for the follow-up GOES-NEXT instruments. He is now developing a efficient and robust statistical algorithm to classify clouds using GOES-8/9 Imager data, even when there are multiple layers and 100% partly cloudy pixels (Molnar and Chesters, 1995). As a public service, Dr. Chesters is maintains popular World Wide Web pages[1] with

[1] http://climate.gsfc.nasa.gov/~chesters/goesproject.html

anonymous FTP access to the previous 24 hours of GOES-8/9 Imager and Sounder data in user-friendly format.

Dr. Chesters will require full time science associate support from a moderately senior contractor, preferably a post-doc. This person is not in-hand, but such support can be found among the many contractors at GSFC supporting remote sensing for the Earth Observing System (EOS) being developed for NASA's Mission to Planet Earth (MTPE).

### Housing

The P.I. is located on-site within the NASA-GSFC Laboratory for Atmospheres, where the flow of GOES data and computing power is readily available. Normal support functions for personal computers and data access will be covered by GSFC's on-site manpower assessment and by the Laboratory for Atmospheres and Climate Branch assessments.

Because of the new restrictions on contract support personnel imposed by NASA-HQ, the contractor will have to be employed through one of the new “manpower exempted” science institutes, such as USRA (Seabrook, MD), JCESS (University of Maryland, College Park) or JCET (university of Maryland, Baltimore). The salary and overhead costs for this arrangement is the same as for regular contractors, but on-site or off-site requirements are murky at this time.

### Computing

The Laboratory for Atmospheres has an on-site the GOES data-reception system in that ingests observations from the new GOES-8 and -9 satellites, and converts the raw data to navigated and calibrated radiances and/or brightness temperatures. This GOES data capture system keeps the most recent 10 hours of GOES raw data on-line, and creates calibrated images and sounding files automatically, which are kept in a 18-hour deep pool for processing.

Sufficient CPU processing power is already available in HP and SGI workstations owned by the Laboratory for Atmospheres and linked together on a FDDI network for rapid data movement. The GOES Sounder generates a modest 19-channel scan of CONUS and the surrounding oceans once every hour, accumulating a few 100 MBytes per day, most of which will be processed and converted to about 10 MB per day of derived products.

We expect to experiment with comparisons between views of the same areas from GOES-8 and GOES-9 satellites, doubling the storage requirements. Some disk space must be kept on-line to compare alternative estimates of the same scenes, as the algorithms are developed. We would buy 20 GBytes of disk storage in three stages, first for the algorithm development, and then for keeping the prototype datasets at the start of the last year of the proposal.

**R&D Costs**

The principal cost is for the salaryplus overhead for the contractor, approximately one-half of $80k per year. On-site manpower costs for the P.I. and contractor at GSFC are assessed at a rate of $8k per man-year. Publications costs in a scientific journal are budgeted at $3k per year, and travel costs to scientific meetings are budgeted at $2k per year for the co-investigator. Hardware and software to support development and store an initial climatology are budgeted at $5k per year. GSFC cost assessments are 9% of the total cost (3% for the Division and 6% for the Climate and Radiation Branch). The Branch assessment covers the cost of the CPU requirements. Inflation is estimated at 5%.

We estimate that about 20 GBytes of hard disk data storage should be purchased to pool the recent GOES data and save the long-term boundary layer and ozone climatology on-line (approximately $10k). Another $5k is requested for hardware and software contingency.

## ONE-PAGE BUDGET SUMMARY

The following table summarizes the costs of establishing and supporting an experienced research associate on-site, co-located with the P-I., mapped onto the USG FYs.

| | 1996 | 1997 | 1998 |
|---|---|---|---|
| **MANPOWER (man-years)** | | | |
| P. I.: Dennis Chesters (NASA) | 0.3 | 0.3 | 0.3 |
| Co-I.: (senior contractor, TBD) | 1.0 | 1.0 | 1.0 |
| **Total man-years** | **1.3** | **1.3** | **1.3** |
| | | | |
| **R&D COSTS ($1000 units)** | | | |
| P. I.: Chesters (NASA employee) | 0 | 0 | 0 |
| Co-I.: (full-time contractor, TBD) | 80 | 84 | 88 |
| Travel for Co-I | 2 | 2 | 2 |
| Publications | 3 | 3 | 3 |
| Hardware & software | 5 | 5 | 5 |
| On-site manpower | 10 | 11 | 12 |
| Division and Branch assessments (9% of total) | 10 | 11 | 12 |
| **Total R&D funds $k** | **110** | **116** | **122** |

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**VITA**
**Dennis Chesters**

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| PRESENT POSITION: | Senior Research Scientist,<br>Climate & Radiation Branch<br>Laboratory for Atmospheres<br>NASA/Goddard Space Flight Center |
| RESEARCH AREA EXPERIENCE: | Infrared satellite sounding; radiation transfer and molecular spectra; satellite data processing systems |
| EDUCATION: | 1965 - B.S. Illinois Institute of Technology<br>1971 - Ph.D University of Maryland |
| PREVIOUS POSITIONS: | 1971-1973 Research and Teaching Associate at Physics Dept., University of Utah<br><br>1973-1978 Senior Analyst with Computer Science Corporation |
| PROFESSIONAL SOCIETY MEMBERSHIPS: | American Meteorological Society<br>American Association for Advancement of Science |

RECENT AWARDS:

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| 1979 | NASA/GSFC Quality Increase |
| 1981 | NASA Group Achievement Award to the VAS Demonstration |
| 1982 | GSFC Exceptional Performance Award |
| 1985 | NASA/GSFC Quality Increase |
| 1987 | GSFC Exceptional Service Award |
| 1989 | GSFC General Recognition Award |
| 1994 | GSFC Performance Award |
| 1994 | GSFC Special Act Award |
| 1995 | GSFC Team Award to the GOES Project |
| 1995 | NASA Exceptional Achievement Award |

SPECIAL EXPERIENCE:

1) Member, AMS Committee on Satellite Meteorology and Oceanography, 1987-1994

2) GOES Project Scientist, 1991-present

**ATTACHMENT**

Chesters, D., A. Mostek and D.A. Keyser, 1986: VAS sounding images of atmospheric stability parameters. *Weather and Forecasting*, **1,** 5-22.